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The HI content of Early–Type Galaxies from the ALFALFA survey

I. Catalogued HI sources in the Virgo cluster

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ABSTRACT

Aims. We are using the Arecibo Legacy Fast ALFA survey (ALFALFA), which is covering 17% of the sky at 21 cm, to study the HI content of Early-Type galaxies (ETG) in an unbiased way. The aim is to get an overall picture of the hot, warm and cold ISM of ETG, as a function of galaxy mass and environment, to understand its origin and fate, and to relate it to the formation and evolution history of these objects.
Methods. This paper deals with the first part of our study, which is devoted to the 8-16 deg. declination strip in the Virgo cluster. In this sky region, using the Virgo Cluster Catalogue (VCC), we have defined an optical sample of 939 ETG, 457 of which are brighter than the VCC completeness limit at $B_T = 18.0$. We have correlated this optical sample with the catalogue of detected HI sources from ALFALFA.
Results. Out of the 389 ETG from the VCC with $B_T \leq 18.0$, outside the 1 deg. region of poor HI detection around M87, and corrected for background contamination of VCC galaxies without a known radial velocity, only 9 galaxies (2.3%) are detected in HI with a completeness limit of 3.5 and $7.6{\times}10^7 M_\odot$ of HI for dwarf and giant ETG, respectively. In addition 4 VCC ETG with fainter magnitudes are also detected. Our HI detection rate is lower than previously claimed. The majority of the detected ETG appear to have peculiar morphology and to be located near the edges of the Virgo cluster.
Conclusions. Our preliminary conclusion is that cluster ETG contain very little neutral gas, with the exceptions of a few peculiar dwarf galaxies at the edge of the ETG classification and of very few larger ETG, where the cold gas could have a recent external origin.

Key words. Galaxies: elliptical and lenticular, cD – Galaxies: ISM – Radio lines: ISM

1. Introduction

Some Early–Type Galaxies (ETG), in particular the massive ellipticals, contain large quantities of hot gas ($T \sim 10^7 K$), which can amount up to at least several $10^{10} M_\odot$ or about 1% of the total stellar mass (see e.g. Mathews & Brighenti 2003, for a review). The presence of warm gas ($T \sim 10^4 K$) in ETG has been studied with several emission line surveys (e.g. Trinchieri & di Serego Alighieri 1991, Goodfrooij et al. 1994, Sarzi et al. 2006), which have detected up to about $10^5 M_\odot$ of ionized gas. Cold gas ($T \sim 10^2 K$) has been detected in a number of ETG from HI 21cm observations (e.g. Knapp et al. 1985, Huchtmeier 1994, Morganti et al. 2006), which find about $10^8 M_\odot$ of neutral hydrogen in some objects. However an unbiased survey of the HI content of ETG is still lacking, mainly because pointed observations have preferentially selected ETG, where the presence of cold gas was likely, and blind HI surveys were not deep enough or did not cover a large enough solid angle in the sky. In fact previous estimates of the HI detection rate for ETG, i.e. of the percentage of ETG detected in HI, vary between 15% (Knapp et al. 1985 and Conselice et al. 2003) and more than 50% (Morganti et al. 2006, see also Table 4 in Bregman et al. 1992).

The interest for studying the content of HI in ETG is based mainly on the possibility that it can give important clues on the formation and evolution of this type of galaxies, also in relation with the other gas phases. Some current models for ETG galaxy formation call for an important role of galaxy merging, which is likely to happen also quite late, when most of the stars have already formed. The presence of cold gas in an ETG would be a sign of possible merging, particularly if it has disturbed morphology and/or kinematics. Furthermore D'Ercole et al. (2000) investigated the effect of tidal encounters on hot gas flows, and found the creation of dense, cold filaments. However, in a previous set of simulations D'Ercole & Ciotti (1998) have studied

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hot gas flows in quite flattened galaxies (S0 or flat Ellipticals), and found that cold filaments are also created at the interface between inflowing and outflowing gas.

The Arecibo Legacy Fast ALFA survey (ALFALFA, Giovanelli et al. 2005 and 2007) is covering in an unbiased way a large area of the sky (7074 square degrees) and is detecting HI sources down to a relatively faint integrated flux density:

$$F_{lim} = 4.46 \times 10^{-3} \times S/N \times \sqrt{W50} \times \sigma_{rms} Jy\ km\ s^{-1} \quad (1)$$

where W50 is the velocity width in $km\ s^{-1}$ of the line profile at 50% of the peak, σ_{rms} is the r.m.s. noise in mJy at 10 $km\ s^{-1}$ resolution and S/N is the required signal–to–noise ratio. Since in ALFALFA, on average, $\sigma_{rms} = 2.0 mJy$, then for S/N=6.5 and $W50 = 100\ km\ s^{-1}$ the limiting flux density corresponds to $3.8 \times 10^7 M_\odot$ of neutral hydrogen at the distance of the Virgo cluster, assumed to be 16.7 Mpc. ALFALFA therefore gives an unprecedented opportunity for studying the cold gas content of ETG in an unbiased way. The strategy we have adopted to exploit this opportunity is briefly the following. We start by selecting a sample of ETG, which should be as complete as possible down to a given galaxy mass or luminosity, and should cover in an uniform way both the cluster and the field environments, since these are likely to influence the gas content in different ways. We then search for HI in these galaxies using the ALFALFA survey data in a two–step approach. The first step is a simple cross–correlation between our ETG sample and the catalogue of detected HI sources produced by the ALFALFA team (e.g. Giovanelli et al. 2007). The second step involves searching in the ALFALFA datacubes for HI detections at the positions – and velocities, when available – of the ETG in our sample. Hopefully this second step can detect sources at a lower S/N ratio than the blind search used by the ALFALFA team to produce their catalogue of detected HI sources. Furthermore the second step can give us a better local estimate of the survey noise at the position of each ETG, and therefore a better estimate of the upper limits for those galaxies where no HI is detected.

In this first paper we report on the results from the first step on the Virgo cluster, for the declination strip between 8 and 16 degrees. Our study is complemetary to the study of the dwarf elliptical galaxies, which Koopmann et al. (in preparation) are conducting among the detected ALFALFA HI sources.

2. Selection of the ETG sample and HI detections

The existence of the Virgo Cluster Catalogue (VCC, Binggeli et al. 1985, and the revision in Binggeli et al. 1993) makes the selection of a sample of ETG in this cluster relatively straightforward. The VCC is essentially complete, independently of morphological type, down to $B_T \sim 18$, which corresponds to $M_B \sim -13.1$ for the assumed distance to the Virgo cluster. However the VCC assigns a multiple morphological type to some of the galaxies, making it difficult to construct a well defined subsample of ETG. We have therefore decided to adopt the morphological classification univoquely given to VCC galaxies by GOLDMine (Gavazzi et al. 2003). In the uncertain VCC cases GOLDMine has decided the classification based on more recent information or on visual inspection of more recent images. We include in our ETG sample all VCC galaxies for which GOLDMine gives a classification type between -3 and 1 (i.e. dS0, dE/dS0, dE(d:E), E-E/S0, S0). We exclude galaxies which have $cz > 3000 km\ s^{-1}$, since they are not members of the Virgo cluster. Finally we limit our analysis to the declination strip from 8.0 to 16.0 degrees, which is the only one for which the catalogue

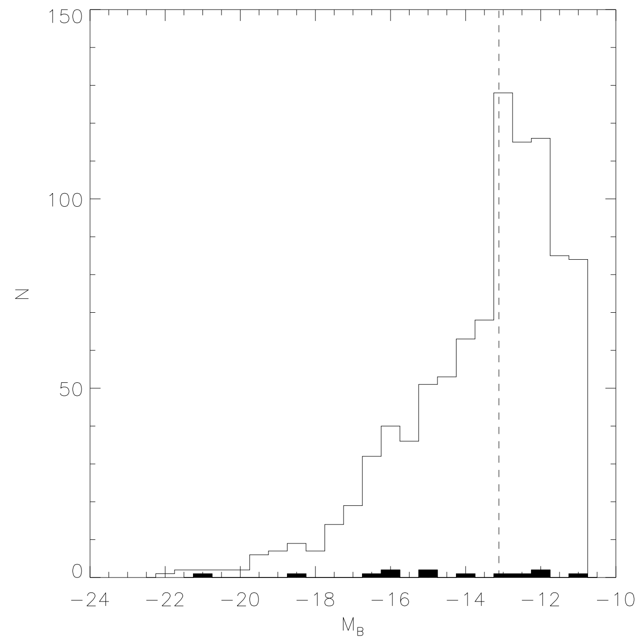

Fig. 1. The absolute magnitude distribution of the ETG detected in HI (filled histogram) with respect to all the ETG in the VCC (empty histogram). The dashed vertical line corresponds to the VCC completeness limit at $B_T = 18.0$.

of detected HI sources from ALFALFA is available (Giovanelli et al. 2007 and private communication). This strip contains the largest fraction of the Virgo cluster area covered by the VCC and more than 70% of its galaxies, centered around M87. Our VCC ETG sample has 939 galaxies, 457 of which are brighter than the completeness limit of $B_T = 18.0$.

We have then cross–correlated this input optical ETG sample with the catalogue of HI detections by ALFALFA in the same sky area (Giovanelli et al. 2007 and private communication). We have used a search radius of 180 arcsec, large enough to avoid possible biases from the uncertainties in the optical and HI positions, and also from the large angular extent of a few galaxies in the catalog. We obtain a total of 13 VCC ETG detected in HI, as listed in Table I. ALFALFA HI detections come at different signal levels (see Table 1): code 1 are detections typically with $S/N \geq 6.5$; code 2 are detections at lower S/N (to ∼ 4.5), which coincide spatially with an optical object of known similar redshift; code 4 are possible detections with still lower S/N.

The ALFALFA HI detection threshold and completeness limit depend on the velocity width (Eq. 1). The average velocity width (W50) for the HI detected ETG is 88 and 235 $km\ s^{-1}$ for the 10 dwarfs and for the 3 other ETG respectively. Since ALFALFA is complete to better than 90% at S/N = 6.5 for dwarfs and at S/N = 8.5 for giants (Saintonge 2007), these completeness limits correspond to 3.5 and $7.6 \times 10^7 M_\odot$ of HI.

Only 9 of the 457 ETG in our sample brighter than the VCC completeness limit (at $B_T = 18.0$) are detected in HI, which corresponds to a percentage of 2.0%, considerably lower than previous estimates. Even if we exclude the 59 ETG with $B_T \leq 18.0$ contained in the one degree region around M87 (see Fig. 2), where the strong radio continuum source reduces considerably the ALFALFA HI detection sensitivity (Giovanelli et al. 2007), and the 11 ETG out of the 133 without a measured radial velocity (i.e. the same percentage of the ETG with measured radial

Table 1. VCC Early Type Galaxies detected in ALFALFA

ID	Other Name	B_T	Type[a] GM	Type VCC	Opt. Pos. RA Dec	$cz_{opt.}$ $km\ s^{-1}$	cz_{HI} $km\ s^{-1}$	M_{HI} $10^7 M_\odot$	Code[b]	M_B	$\log(M_{HI}/L_B)$ $M_\odot/L_\odot$
VCC 21	IC 3025	14.75	-3	dS0(4)	121023.0+101118	486	485	5.3	2	-16.36	-1.0
VCC 93	IC 3052	16.3	-1	dE2	121348.1+124126	910	841	3.5	1	-14.8	-0.6
VCC 209	IC 3096	15.15	-3	dS0?	121652.4+143055	1208	1263	3.6	1	-15.96	-1.0
VCC 304		16.3	-1	dE1 pec?	121843.8+122308	155	132	3.2	1	-14.8	-0.7
VCC 355	NGC 4262	12.41	1	SB0	121930.6+145238	1359	1367	49.1	1	-18.70	-1.0
VCC 421		17.0	-1	dE2	122030.7+133109		2098	3.4	2	-14.1	-0.3
VCC 881	NGC 4406	10.06	0	$S0_1(3)$/E3	122611.8+125646	-244	-302	8.0	2	-21.05	-2.7
VCC 956		18.75	-1	dE1,N:	122656.4+125741		2151	9.2	1	-12.36	0.8
VCC 1142		19.0	-1	dE	122855.2+084855		1306	4.7	1	-12.1	0.6
VCC 1202		20.0	-1	dE?	122933.6+131146		1215	14.5	1	-11.1	1.5
VCC 1964		18.0	-1	dE4:	124319.7+085710		1495	4.3	4	-13.1	0.3
VCC 1993		15.3	0	E0	124412.0+125631	845	925	4.5	2	-15.8	-0.9
VCC 2062		19.0	-1	dE:	124759.9+105815	1146	1141	32.7	1	-12.1	1.5

[a] GOLDMine type: -3=dS0 -2=dE/dS0 -1=dE(d:E) 0=E-E/S0 1=S0
[b] See the text for explanations

velocity which have $cz > 3000\ km\ s^{-1}$), which are probably background galaxies, the detection rate increases only slightly, to 2.3%, which is still much lower than previous estimates. In addition we have estimated the possible contamination on the complete VCC sample due to field galaxies within 3000 $km\ s^{-1}$, based on the luminosity density and function given by Binggeli (1988) for the cluster and the field. We derive an average value for this contamination of 1.4%, not depending strongly on the apparent magnitude limit. Its effect on the detection rate is negligible. Furthermore Binggeli et al. (1985) with the updates in Binggeli et al. (1987) consider uncertain the cluster membership for 28 galaxies out of the 457 ETG in our sample brighter than the completeness limit of $B_T = 18.0$. Some of these are likely background galaxies, with a percentage which is then smaller or equal to 6.1%.

Figure 1 shows the distribution of absolute B-band magnitudes for the ETG in our whole sample, and for those that are detected in HI. Considering the accuracy allowed by poissonian statistics for the small number of detected galaxies, there is no evidence that the detection rate depends on the galaxy luminosity: for example, 2 out of 55 ETG brighter than $M_B = -17.0$ ($3.6 \pm 2.5\%$) and 7 ETG out of 402 with $-17.0 < M_B \leq -13.1$ ($1.7 \pm 0.7\%$) are detected in HI. The ratio between the amount of neutral hydrogen and the B-band luminosity varies by about 4 orders of magnitude among the ETG detected in HI (see the last column of Table 1 and Figure 2). The strong correlation between the M_{HI}/L_B ratio and the B-band luminosity is mostly induced by the ALFALFA HI detection limits. In particular optically faint ETG with a small M_{HI}/L_B ratio would not be detected by ALFALFA. However we remark on the absence of bright ETG with a high M_{HI}/L_B ratio, similar to that of the dwarf ETG, which would have been easily seen, if they existed.

We also notice the large fraction of peculiar (or morphologically uncertain) ETG among those with HI (see the VCC type in Table 1). One can argue that the presence of peculiarities enhances the chances that an ETG contains neutral hydrogen (van Gorkom & Schiminovich 1997) and that bona fide elliptical and lenticular galaxies would have an HI detection rate even lower than reported here. In fact several of the detected galaxies are at the border of the ETG classification.

Figure 3 shows the position in the sky of the ETG detected in HI. Even considering the lower HI detection sensitivity around M87 (the dark grey circle in Fig. 3), it is apparent that the ETG detected in HI are preferentially at the edges of the Virgo cluster and in the region of the so–called cloud M in the North–Western side of the Virgo cluster (Ftaclas, Fanelli & Struble 1984), where the X-ray surface brightness is low (Böhringer et al. 1994) and spiral galaxies appear to be less HI–deficient than in the rest of the cluster (Gavazzi et al. 1999). An important result is also that 809 ETG of our sample in the Virgo cluster (391 with $B_T \leq 18.0$) have been well observed by ALFALFA (they are out of the 1 deg. region around M87) and have not been detected, i.e. they contain less neutral hydrogen than the ALFALFA completeness limit of 3.5 and $7.6 \times 10^7 M_\odot$ for dwarf ETG and for the other ETG, respectively.

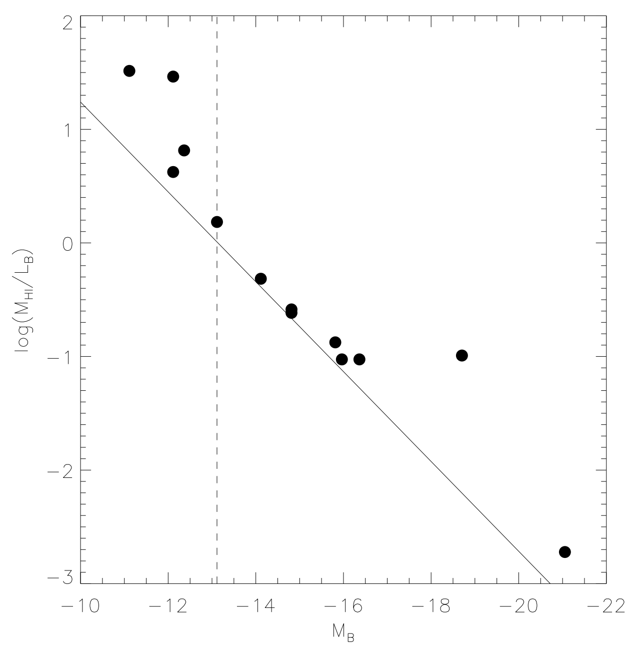

Fig. 2. The dependence of the ratio between the neutral hydrogen mass and the B–band luminosity with the B–band absolute magnitude for the 13 detected ETG. The dashed line is the VCC completeness limit at $B_T = 18.0$, and the continuous line represents a detection limit of $3 \times 10^7 M_\odot$ of HI.

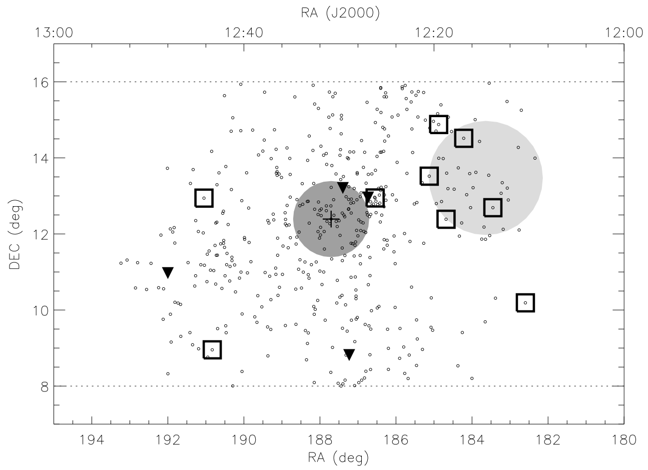

Fig. 3. Position of the Early Type galaxies in the 8-16 deg. declination strip in the Virgo cluster: the dots are the ETG in the VCC with $B_T \leq 18.0$; squares and triangles are the ETG detected in HI, with $B_T \leq 18.0$ and with $B_T > 18.0$, respectively. The cross marks the position of the central cD galaxy (M87), and the dark grey circle is the 1 deg. radius zone where the HI detection is disturbed by M87 (Giovanelli et al. 2007). The light grey circle shows the position of the M cloud (Ftaclas, Fanelli & Struble 1984).

3. Notes on individual objects and comparison with previous work

The dE4 galaxy VCC 748 has a tentative HI detection (code=4) in the ALFALFA catalogue. However it has been reobserved at 21cm as part of the follow–up programme and not detected to a $\sigma_{rms} = 1.46\ mJy$ (Kent et al. in preparation). Using S/N=6.5 and assuming a velocity width of 88 km/s (the average for the detected dwarf ETG) this corresponds to an upper limit to the 21cm flux density of 0.4 $Jy\ km\ s^{-1}$ and to an upper limit to the HI mass at the distance of the Virgo cluster of $2.6 \times 10^7 M_\odot$. The other ETG detected with code=4 (VCC 1964) has not yet been reobserved, and its detection should be taken as only tentative.

We note that the most optically luminous detected galaxy (VCC 881, also NGC 4406 and M86) is also the ETG with the largest Hα luminosity of the sample of ETG with hot gas studied in Hα by Trinchieri & di Serego Alighieri (1991). The ionized gas in this object has a complex structure of filaments and arcs, possible sign of a recent merging event.

We have carried out an analysis of the previous HI detections in the VCC area, not detected in the ALFALFA catalogue, in order to understand the possible origin of the discrepancy between our HI detection rate for ETG and those previously claimed. The GOLDMine compilation reports HI detections for 11 ETG of our extended sample of 939 galaxies. Only two of these (VCC 355 and VCC 2062) are present in Table I, i.e. are also detected by ALFALFA. For these two galaxies the previous observations (Burstein et al. 1987, and Hoffman et al. 1993) agree reasonably well with the ALFALFA measurements. Of the remaining 9 ETG, only two, VCC 1630 and VCC 575, have a previous HI detection at a very low level, below the ALFALFA detection limit (Lake & Schommer 1984). For all the other 7 ETG (VCC 608, VCC 763, VCC 1226, VCC 1619, VCC 1949, VCC 2012 and VCC2095) a careful inspection of the literature reveals the inconsistency of the previous HI detections. In particular, VCC 608 (NGC 4323) was observed by Huchtmeier & Richter (1986), who state in a note that all the HI flux in the area comes from NGC 4321. VCC 763 (NGC 4374) was observed by Davies & Lewis (1973), who probably had baseline problems. The best upper limit for the 21cm flux of VCC 763 is 7.5 $Jy\ km\ s^{-1}$ by Heckman et al. (1983). VCC 1226 (NGC 4472) was tentatively detected at 2σ by Davies & Lewis (1974), but the best upper limit for the 21cm flux is 0.10 $Jy\ km\ s^{-1}$ by Bregman et al. (1988). Peterson (1979) claimed a detection for VCC 1619 (NGC 4550), but this galaxy was not detected in HI by Krumm & Salpeter (1979, $S_{21cm} < 2.1 Jy\ km\ s^{-1}$) nor by Duprie & Schneider (1996, $S_{21cm} < 1.3 Jy\ km\ s^{-1}$). Huchtmeier & Richter (1986) claimed a detection for VCC 1949 (NGC 4640), but nothing is visible in their spectrum, and the galaxy was not detected by Haynes & Giovanelli (1986, $S_{21cm} < 0.9 Jy\ km\ s^{-1}$). VCC 2012 was detected by Huchtmeier & Richter (1986) but with the incredible velocity width of $472 km\ s^{-1}$ for a dE3 galaxy. The low level detection of VCC 2095 (NGC 4762) by Krumm & Salpeter (1976) was later disclaimed, while Giovanardi et al. (1983) give an upper limit for the 21cm flux of 0.5 $Jy\ km\ s^{-1}$. Therefore there is no real discrepancy between the previous HI measurements and the results of ALFALFA, as far as the VCC ETG in our declination strip are concerned.

In order to understand the reasons for our much lower detection rate, we analyse in more detail the recent HI study of Morganti et al. (2006), who have surveyed the HI content of the elliptical and lenticular galaxies of the SAURON sample. The SAURON team (de Zeeuw et al. 2002) has selected from the Lyon-Meudon Extragalactic Database (LEDA, Paturel et al. 1997) a sample of 29 E and 51 S0 galaxies in clusters, and 47 E and 86 S0 galaxies in the field with the following criteria: $cz \leq 3000 km\ s^{-1}$, $M_B \leq -18.0$, $-6.0^\circ \leq Dec. \leq 64^\circ$. Out of these 213 galaxies they have selected a representative sample of 12 E and 12 S0 galaxies in clusters, and 12 E and 12 S0 galaxies in the field. They show that the representative sample of 48 galaxies has no bias in the M_B vs. ellipticity plane with respect to the total sample of 213 galaxies. Morganti et al. (2006) have concentrated on the SAURON subsample of 24 galaxies in the field and observed all those with declination larger than 23 degrees, as well accessible from Westerbork. They have however excluded NGC 3032, which is a SAB0, and included NGC 4150 and NGC 4278, which belong to the cluster SAURON sample. They have then observed at 21cm 4 E and 8 S0 galaxies. They detect HI in 4 E and in 5 S0 galaxies, with a detection rate of 75%. Their pointed 21 cm observations are deeper than the ALFALFA survey. Still, at the ALFALFA detection level, 3 E and 3 S0 are detected out of the 12 galaxies observed, i.e. a detection rate of 50%. We have however to consider that the SAURON sample is selected at brighter magnitudes ($M_B \leq -18.0$) than ours ($M_B \leq -13.11$). Reducing our samples to the same magnitude limit as SAURON, ALFALFA detects HI in 2 ETG out of 32 (outside the 1 deg. region around M87), a detection rate which is still 8 times lower than the one of Morganti et al. (2006). Part of this difference might be due to the well–known higher HI detection rate in the field than in the clusters (e.g. Solanes et al. 2001, and references therein).

4. Conclusions

We are exploiting the great opportunity given by the ALFALFA survey to study in an unbiased way the HI content of ETG. The cross–correlation of the ETG in the 8–16 deg. declination strip of the VCC and the catalogue of ALFALFA detected sources for the 8–16 deg. declination strip on the Virgo cluster has resulted in 13 ETG detected in HI, with a survey completeness limit of

3.5 and $7.6 \times 10^7 M_\odot$ of HI for dwarf and giant ETG, respectively. Only two of these ETG were already known to contain neutral hydrogen. The HI detection rate for ETG down to the VCC completeness limit of $B_T = 18.0$ varies between 2.3 and 2.0%, depending on whether or not one considers the region of lower HI detection sensitivity around M87 and the correction for background galaxies. This detection rate is considerably lower than previous claims, based on incomplete surveys, and there is no clear evidence that it depends on the galaxy luminosity. The HI detected galaxies tend to lie at the edges of the cluster and to have a peculiar morphology.

Within the detection limits of ALFALFA, which affect differently large and dwarf ETG, our preliminary conclusion is that cluster ETG contain very little or no neutral gas, with the exception of some peculiar dwarfs, which are at the edge of the ETG morphological classification, and of very few larger galaxies for which the gas has a recent external origin. Given the very few large ETG with HI, we suggest that the ETG merging rate with gas reach objects should be very low in a cluster like Virgo.

We are currently improving the HI detection for the ETG of our optical VCC sample by a search in the ALFALFA datacubes at the optical positions and velocities, when available, which will be the subject of a future paper (Grossi et al., in preparation). We are also planning to investigate the HI content of a complete sample of ETG in the field.

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